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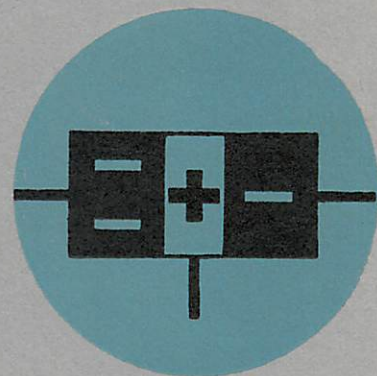
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Properties of junction transistors

by

K. D. Smith



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PROPERTIES OF JUNCTION TRANSISTORS

K. D. SMITH

Bell Telephone Laboratories, Murray Hill, New Jersey

Abstract.—The development of an n - p - n junction transistor was announced to the public a little more than a year ago. This paper reports results of efforts to improve the characteristics and reproducibility of junction transistors of the development type M1752, and discusses the relations of some of the design variables to the equivalent circuit parameters of the device. A discussion will be given of the frequency response and temperature limitations of the models presently being fabricated, with some indication of the feasibility of higher power transistors. Results of early life tests of the M1752 transistor will be presented.

I. INTRODUCTION

In the four year period since the disclosure of the point contact transistor by Bardeen and Brattain, the theoretical and practical aspects of transistor design have been carried forward at a rapid pace. The word "transistor" now covers a rapidly expanding field, in which new structures appear most frequently.

The n - p - n junction transistor was announced in July, 1951¹ and the characteristics of experimental models have been described². This paper will report results obtained with moderate quantity developmental units, and will consider a few of the design aspects of junction transistors made from single crystal germanium of multiple conductivity type³. Some of the factors of importance in increasing the power handling capabilities of junction transistors are mentioned.

Before considering a particular type of transistor, it will be well to establish the family relationships between the various transistor types. Present day transistor triodes may be classed as point contact or as junction devices. By a point contact transistor, we mean one in which the transistor is constructed by applying two metal pressure contacts to semiconductor material of a single conductivity type. It is customary to "form" the transistor after applying the metal contacts, but no physical bond is made. Junction transistors are those in which regions of the semiconductor material are of different conductivity type. Usually the wire connections to these regions are welded or soldered "ohmic" connections.

The n and p conductivity regions may be formed during growth of a germanium crystal³ or local regions of p type material may be produced on an n -type base by suitable processes⁴. The essential feature of the junction transistor triode is that a thin layer or stratum of one conductivity type separates two regions of opposite type. From a practical standpoint it is of course necessary to make electrical connection to all three regions. A wide range of structural designs is possible, still keeping the same functional configuration. Figure 1 shows three development model junction transistors, with an aspirin tablet as a size scale.

The transistors to be considered in this paper are shown schematically in Fig. 2; the mode of operation may be briefly described as follows:

The collector-base junction is reverse biased by the positive collector voltage, and very little current flows in the absence of emitter current. If emitter current does flow, electrons cross the emitter-base junction into the base, where they are minority carriers, and travel by diffusion. If the base layer is sufficiently thin, most of these

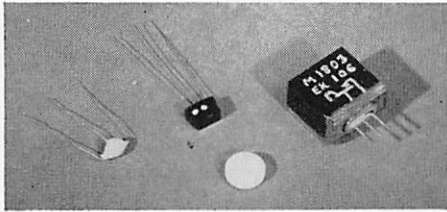


Fig. 1—Photograph of development model junction transistors.

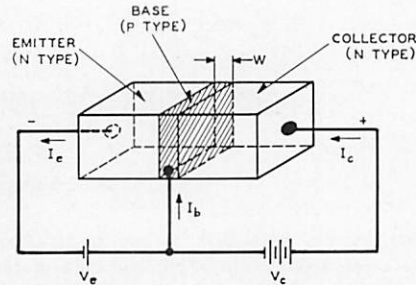


Fig. 2—Schematic diagram of n-p-n transistor.

electrons will diffuse over to the collector junction and become part of the collector current. The base may be considered as a membrane which is semi-transparent to electrons. The electrons arriving at the collector barrier from the emitter side are drawn through the barrier by the positive collector bias, which at the same time prevents passage of electrons in the opposite direction. The number of electrons injected by the emitter can be controlled by the small forward bias between emitter and base, which allows high power gains to be realized.

The current flowing in the base lead is but a small fraction of that in either the emitter or the collector circuit. In grounded emitter operation, the base may be considered as a positive grid, which draws some current, but which controls a much larger current from collector to emitter, giving high current amplification.

II. GENERAL DESIGN CONSIDERATIONS

The highly simplified operational explanation just presented is of course not suitable

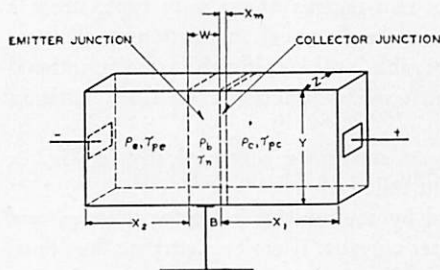


Fig. 3—Material properties used in transistor design.

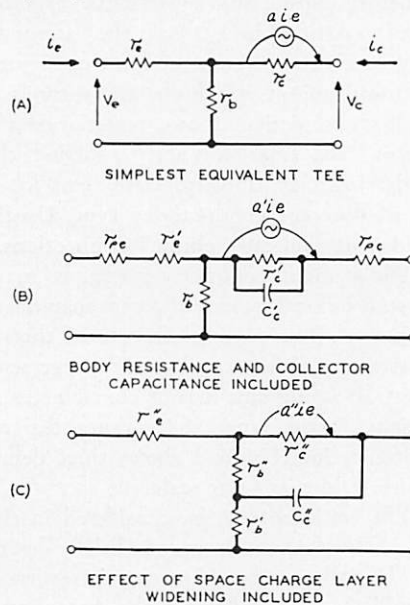


Fig. 4—Equivalent tee circuits for junction transistor.

for even a first order design analysis. For design purposes it is necessary to know what performance features are important, and how these are related to the design parameters. The design of a device then becomes a series of compromises, in which a practical balance is struck between desirable performance on the one hand, and practical limitations of material and processes on the other. In Table I some of the factors of importance in design are shown in the left hand column, and features of interest in evaluating performance are in the right hand column. While it is beyond the scope of this paper to attempt a complete analysis of the interrelations of the variables listed in Table I, some of the simpler relations will be discussed.

TABLE I
FACTORS OF IMPORTANCE IN DESIGN AND IN
APPLICATION OF N-P-N TRANSISTORS

<i>Design Factors</i>	<i>Features of Interest to User</i>
MATERIAL PROPERTIES	EQUIVALENT CIRCUIT
Collector resistivity, ρ_c	PARAMETERS α, τ_c, τ_e, τ_b, C_o
Base resistivity, ρ_b	Power gain
Emitter resistivity, ρ_e	Current gain
Minority carrier lifetime in	Large Signal Characteristics
Collector, τ_{pi}	Frequency response
Base, τ_n	Noise
Emitter, τ_{ps}	Microphonics
Width of base, w	Zener voltage, V_z
Width of space	Saturation Current, I_{co}
Charge layer, X_m	Temperature effects
PHYSICAL DESIGN	Thermal time constant
Area of Junction, A	Power dissipation
Length of Collector	Reliability
Length of Emitter	Life
Lead Arrangement	Ruggedness
Surface protection	Stability
Packaging	Efficiency
Thermal Dissipation	Photo electric effects
Physical Size	Transient effects
PROCESS VARIABLES	

Figure 3 shows schematically some of the quantities in the left column of Table I, and Fig. 4 shows three equivalent circuit Tee representations for the grounded base connection. Characteristics of the various circuit connections, and relations of the terminal impedances to the Tee network elements have been discussed by Wallace and Pietenpol² and will not be repeated here.

Relations Between Design Parameters and Four-pole Elements

The simplest equivalent circuit, Fig. 4(A), shows three resistive elements and a current generator, and is applicable for first order analysis at low frequency. The r_e arm represents the forward resistance of the emitter junction. If the emitter junction is assumed to have similar properties at all points in the YZ plane, and if the current for each elemental area of the junction is the same, then

$$(1) \quad r_e = \frac{kT}{q I_c} = \frac{25.9}{I_c (ma)} \text{ at room temperature.}$$

where k = Boltzmann's constant
 T = Absolute Temperature
 q = charge of one electron

It may be noted that r_e does not depend on the area of the emitter junction, at least within the assumptions leading to the above equation.

The second element, r_b , is nearly the ohmic resistance of the base layer and base contact, and so depends on the resistivity of the base, ρ_b , and on the physical dimensions and the geometry. For low base resistance, a most desirable feature, the resistivity of the base layer should be low, and the dimension w should be large. It will be seen later that these objectives cannot be met without other sacrifices.

The third element of the simple representation is the collector resistance, r_c . In the simple theory, under reverse bias conditions r_c should approach infinity, since it would be limited mainly by the high but finite surface leakage resistance across the junction. Recent work by J. M. Early⁵ indicates, however, that a significant reduction in r_c is caused by narrowing of the base layer as the collector voltage is increased. This effect, which also modifies the r_e and r_b elements, is considered later in this section.

The remaining element in the simple equivalent circuit is the short circuit current gain factor⁶, a . Actually the current gain factor used in design is

$$(2) \quad a = \frac{\partial I_c}{\partial I_e} \bigg|_{V_c} = \frac{r_m + r_b}{r_c + r_b}$$

while

$$a = r_m / r_c$$

Since r_m and r_c for junction transistors may be more than a thousand times r_b , the difference is usually negligible, and it is the short circuit gain, a , which is measured.

The factor a is related to the design parameters by the expression^{1,7}

$$(3) \quad a \equiv \gamma \beta a_i$$

where

$$\gamma = \frac{1}{1 + \frac{\rho_e}{\rho_b} \frac{L_b}{L_e} \tanh \frac{w}{L_b}} \doteq \frac{1}{1 + \frac{\rho_e w}{\rho_b L_e}}$$

and

$$\beta = \operatorname{sech} \frac{w}{L_b} \doteq 1 - \frac{w^2}{2L_b^2}$$

(when $w \ll L_b$)

a_i = collector multiplication factor

$a_i = 1$ when ρ_e is very much lower than for intrinsic material.

The quantities L_b and L_e are the diffusion lengths in the base and emitter, respectively, and are related to the minority carrier lifetime and the diffusion constant, as

$$(4) \quad L_p = (D_p \tau_p)^{1/2}, L_n = (D_n \tau_n)^{1/2}$$

the diffusion length being the average distance which a minority carrier will travel in any given direction before recombining, if it has a lifetime τ .

It is evident from (3) that γ can be made to approach unity if $\rho_e \ll \rho_b$ and if $w \ll L_e$. Gamma is the emitter efficiency term, that is, the fraction of the total emitter current which is carried by minority carriers into the base region. A fraction $(1 - \gamma)$ of the total emitter current is hole current from the base into the emitter, which does not cause any change in collector current.

The factor β is a transport term, being the fraction of total electrons emitted into the base which diffuse across and are collected at the collector junction. A smaller fraction $(1 - \beta)$ of the emitted electrons recombine before reaching the collector. In order to make β approach unity it is necessary that $w \ll L_b$, which can be effected by making w very small or L_b long, or both.

In Fig. 4(B) the ohmic resistances of the emitter and collector material have been included, and the collector capacitance is shown. The resistance of the emitter and the collector body material may usually be neglected in comparison to the respective junction resistances. The collector capacitance will be of importance except at low frequencies. It depends on the junction area, the rate of change of impurity concentration, and the applied voltage. If the impurity concentration gradient is linear across the space charge layer,

$$(5) \quad C_c = 3 \times 10^{-3} \left(\frac{a}{V} \right)^{1/3} A$$

where C_c = Collector junction capacitance in μf

a = The impurity gradient $\frac{d}{dx} (N_d - N_a)$

V = Applied voltage

A = Junction area in cm^2

and if the junction is an abrupt transition from very low resistivity material of one type to high resistivity material of opposite type, the junction capacitance will vary inversely as the square root of the applied voltage, rather than as indicated above⁸.

In Fig. 4(C) the simple circuit is shown modified to include the effects of widening of the space charge layer with increase of collector potential, as suggested by Early⁵.

The space charge layer, X_m in Fig. 3, extends partly into the base region, and partly into the collector. As the collector voltage changes, therefore, the effective base layer width (in which the minority carriers travel by diffusion) is also changed. The modulation of base layer width gives rise to a collector conductance term, g_c , and to a voltage feedback factor, μ_{ec} where

$$(6) \quad g_c^* = \frac{I_e}{w} [2(1 - \beta) + (1 - \gamma)] \frac{\partial w}{\partial V_c}, \text{ and}$$

$$(7) \quad \mu_{ec} = \frac{\partial V_e}{\partial V_c} = \frac{kT}{qw} \frac{\partial w}{\partial V_c}$$

The elements of Fig. 4(C) then become

$$(8) \quad r_e'' = r_e - (1 - \alpha) \mu_{ec} r_c^* a$$

$$(9) \quad r_c'' = r_c^* (1 - \mu_{ec})$$

$$(10) \quad r_b'' = \mu_{ec} r_c^* = \frac{r_e}{(1 - \alpha) + (1 - \beta)}$$

$$(11) \quad a'' = \frac{a - \mu_{ec}}{1 - \mu_{ec}}$$

The above relations indicate that the use of thin base layers of high resistivity will result in significant effects because of space charge layer widening. In particular, it will be expected that the measured values of r_e and r_c will be lower than given by

* $r_c^* = 1/g_c^*$.

the simple theory, that r_b will be higher, and that α will not be significantly changed. An additional point of interest is that since C_o is not in series with r_b , low frequency measurements of the equivalent circuit parameters will not adequately characterize the performance at high frequency.

Zener Voltage, Saturation Current, Temperature Effects

The Zener voltage^{9,10} of a reverse biased junction is that voltage which produces a maximum field just sufficient to transfer valence electrons into the conduction band. It is of considerable design importance, being the maximum reverse potential which can be applied to the junction without excessive current flow. High Zener potentials may be achieved by making the space charge layer wide, either by using high resistivity material for the base or the collector or both, or by a gradual transition from n type to p type material. These measures also reduce the junction capacitance. The Zener field in germanium is considered to be about 2×10^5 volts/cm, so that a junction having a Zener potential of 100 volts would have a space charge layer in the order of 5×10^{-4} cm at this potential.

When no emitter current is passed, and the collector junction is reverse biased, a small current flows from collector to base. This saturation current, I_{co} , may be a few microamperes for good transistors, or much larger if the material or the process is defective. In practical transistors the measured saturation current is found to contain a constant and an ohmic component. The constant term (when $V_o > 0.1V$) should be, at room temperature

$$(12) \quad I_s = 0.24 \times 10^{-6} A \left[\frac{\rho_o}{\sqrt{\tau_o}} + \frac{\rho_b w}{13 \tau_b} \right]$$

where the terms inside the bracket represent thermally generated minority carriers which diffuse into the junction. This current may be reduced by the use of low resistivity material of high carrier lifetime. The thermal generation of carriers is an exponential function of temperature, and this component of the saturation current increases at a rate of about ten per cent per °C in the normal working temperature range.

The ohmic component of I_{co} may result from surface leakage across the space charge region, or possibly from local defects in the germanium material. The ohmic component may of course be separated from the true saturation current by measurements at different collector potentials. In presently available transistors, effects of surface recombination and of leakage conductance are not negligible, and current values as low as would be predicted from (12) are not normally observed. The measured temperature coefficient of I_{co} is less than the theoretical value, averaging about seven per cent per °C for the M1752 transistor.

While other parameters are much less temperature sensitive than the saturation current, the limitations imposed by temperature effects are still significant. As the temperature is raised, r_c decreases, r_b and r_e increase, and α increases slightly. The reduction in r_c is usually the most serious effect, limiting the useful working temperature to about 70°C for germanium junction transistors.

Frequency Response, Noise, Reliability

The factors responsible for high-frequency cutoff in junction transistors have been discussed by Wallace and Pietenpol², where the importance of the effect of collector

capacitance was shown. In some applications, the high-frequency alpha cutoff is the more important factor. The alpha cutoff frequency $f_c(a)$ is defined as the frequency at which the transmission of the device (into a short circuit load) is reduced three db from its low frequency value. The cutoff frequency is given by,

$$(13) \quad f_c(a) = \frac{D_b}{\pi w^2}$$

where D_b is the diffusion constant for minority carriers in the base, and w = thickness of base layer.

For a base layer of p -type germanium this reduces to

$$(14) \quad f_c(a) \approx \frac{4.5}{w^2}$$

where f_c is in megacycles and w is in mils.

It is evident that high frequency response in this structure can only be obtained with very thin base layers.

Two other effects of interest in high frequency operation may be mentioned. Where the transistor is used in grounded emitter circuits, the signal is applied to the base, and the current gain at low frequencies is:

$$(15) \quad G.G. = \frac{a}{1-a}$$

As the frequency increases, the reactive component of base current becomes dominant, and the current gain is rapidly reduced. The short circuit transmission cutoff of the grounded emitter connection then is:^b

$$(16) \quad f_c'(a) = (1-a) f_c(a).$$

Thus the circuit cutoff may be only a few tens of kilocycles for transistors having alpha values near unity, where the $(1-a)$ term of (16) approaches zero.

The collector junction capacitance is in shunt with r_c , and this combination is in series with r_b . At high frequency, the realizable collector circuit impedance is limited by losses in the C_c , r_b series combination. To achieve satisfactory high frequency narrow band circuits, it is desirable to reduce both C_c and r_b to the minimum practicable values.

Correlation of junction transistor noise with design parameters is at present in an early stage. Some measurements showing the range to be expected for the M1752 development model are given in the next section.

Factors of primary importance in transistor applications are reliability and life. Since the junction transistor consists of three leads connected to a single piece of semiconductor material, with nothing to wear out, the design problems of the device are those of mechanical durability of the structure and chemical stability of the germanium surface and the lead connections. Although considerable progress has been made in these regards, it is evident that improvements can and will be made. Measurements over a period of time on a group of development model junction transistors are given in a later section.

III. RESULTS OF MEASUREMENTS

The M1752 development model n - p - n transistor is shown in the center of Fig. 1.

^bFrequency cutoff in transistors will be discussed more fully in a paper by D. E. Thomas, to be published in *Proc. I.R.E.*, November, 1952.

547 DEVELOPMENT MODEL M1752
NPN TRANSISTORS

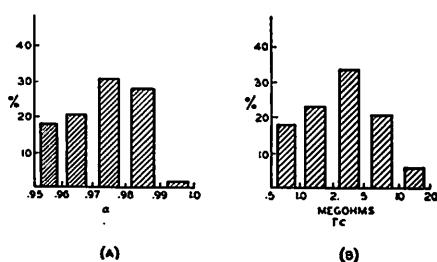


Fig. 5—Distribution of α and r_c values, development model M1752 transistor.

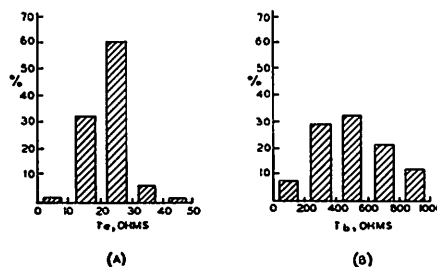


Fig. 6—Distribution of r_e and r_b values.

This transistor is designed for low power applications at low and moderate frequencies. Several hundred of these M1752 transistors have been made to provide units for study and to assay design and fabrication techniques. The units were all tested at a nominal operating point of V_c 4.5 V, I_e 1.0 ma, and were required to pass the tentative test limits shown in Table II. Sample measurements were made of collector capacitance, frequency response, noise, and dependence of parameters on temperature.

The distribution of measured values of the parameters indicated in Table II is shown in Figs. 5, 6, and 7 where the ordinate is in each case the per cent of the group lying between the limits indicated. In Fig. 5(A) which shows the α values for 547 transistors, it is evident that the distribution is not well centered in the 0.95 to 1.0 range, although the median value ($\alpha = .973$) is near the center.

TABLE II
TENTATIVE TEST LIMITS, M1752 MODEL PRODUCTION

Quantity Measured	Limits	Conditions
Current Gain Factor, α	$0.95 < \alpha < 1.0$	$V_c = 4.5v., I_e = 1.0 \text{ ma}$ $f = 1000 \sim$
Collector Resistance, r_c	$0.5 \text{ meg} < r_c$	$V_c = 4.5v., I_e = 1.0 \text{ ma}$ $f = 100 \sim$
Emitter Resistance, r_e	$r_e < 50\omega$	$V_c = 4.5v., I_e = 1.0 \text{ ma}$ $f = 100 \sim$
Base Resistance, r_b	$r_b < 1000\omega$	$V_c = 4.5v., I_e = 1.0 \text{ ma}$ $f = 100 \sim$
Saturation Current, I_{co}	$I_{co} < 30\mu A$	$V_c = 4.5, I_e = 0$

Figure 5(B) shows the distribution of measured values of collector resistance. Here the five groups are chosen from a logarithmic plot, as the range of collector resistances is very large. It may be noted that here, as for the α plot, the application of the lower limit has resulted in appreciable shrinkage. This means that for these parameters the material, process, and test limits were not in good balance, and that these should be studied in order to permit improved yields.

Figure 6(A) gives measured values of r_e at an emitter current of one milliampere. A significant fraction, slightly more than 30% of the values, are below 20 ohms, where the simple theory would require 25.9 ohms plus the body resistance of the emitter. This shift in the direction of lower emitter resistance is in accord with Early's theory, outlined in the previous section.

Figure 6(B) shows r_b to follow a rather smoothly graded distribution, centered

547 DEVELOPMENT MODEL
M1752 TRANSISTORS

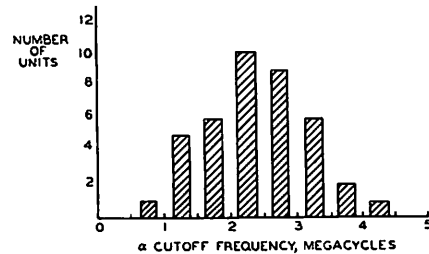
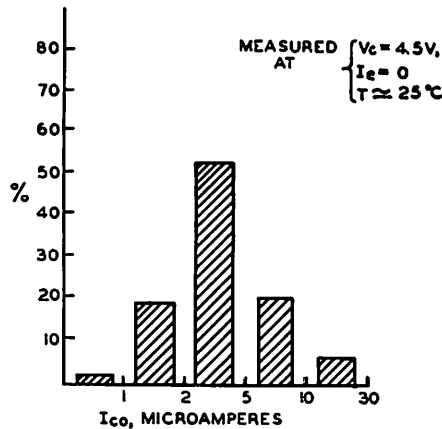


Fig. 7—Distribution of values of saturation current, I_{co} . Fig. 8—Alpha frequency cutoff, M1752 transistor.

in the 500 ohm region. The r_b measured here includes the r_b' term indicated in Fig. 4(C), and the values are thus higher than the r_b which would be computed from the base layer dimensions and resistivity.

Figure 7 shows the results of saturation current measurement, in which the groups are selected on an approximately logarithmic basis. The rather wide range of values indicates a considerable spread in material, process, or both. It may be noted, however, that at the cost of an additional 5% shrinkage, the upper limit of I_{co} could have been made 10 microamperes. While it is certain that further improvement can be obtained, saturation currents of this order are tolerable in many applications.

The median values for the 547 transistors used in the above tests were:

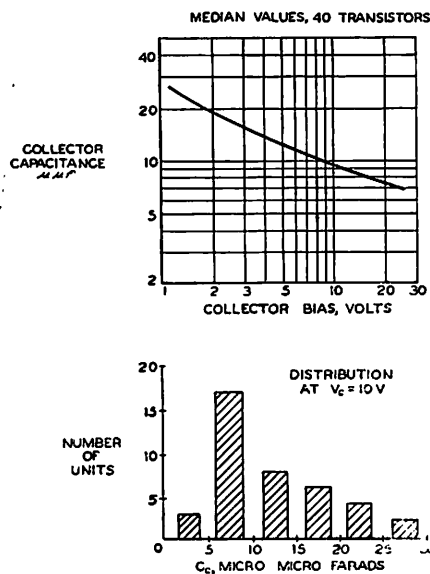


Fig. 9—Collector capacitance measurements.

$$\begin{aligned} \alpha &= 0.973, r_c = 2.7 \text{ megohms}, r_e = 24 \text{ ohms}, \\ r_b &= 480 \text{ ohms}, I_{co} = 3.3 \text{ microamperes.} \end{aligned}$$

The measurements were made at low frequency, after an aging period of 24 hours at a power dissipation of 25 milliwatts. Information obtained in life tests of a smaller group of M1752 transistors suggests that a longer aging period should be used. These tests are discussed in a later section.

Figure 8 shows the distribution of alpha cutoff, measured on a sample of 40 transistors. The rather wide range of cutoff frequency is in reasonable agreement with predictions based on measured values of w , and could be reduced by selection of material.

Measurements of collector junction capacitance, C_c , of 40 transistors are shown in Fig. 9. Figure 9(A) gives the median capacitance vs. collector bias potential. The slope of this curve is slightly steeper than the value of $1/3$ which would be expected for a junction having a linear concentration gradient. Figure 9(B) gives the distribution of measured capacitance values at a collector potential of 10 volts. Variation of capacitance from unit to unit is due to variation of junction area and differences in concentration gradient at the junction. The transistors used in these capacitance measurements were selected to cover the full range of material properties used in fabrication of the M1752, hence give wider dispersion of capacitance values than would be obtained from more uniform material. Measurements of area, capacitance, and Zener voltage of individual transistors show qualitative agreement with theory, hence if the area and the Zener voltage are measured, the capacitance may be estimated.

The results of parameter measurement of fourteen M1752 transistors over a limited

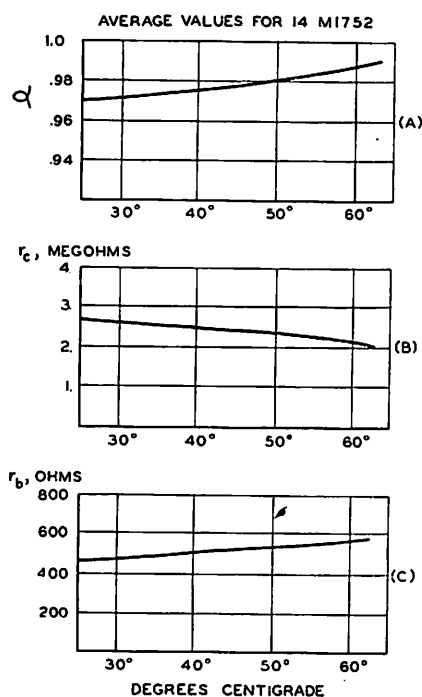


Fig. 10—Effect of temperature on α , r_c , r_b .

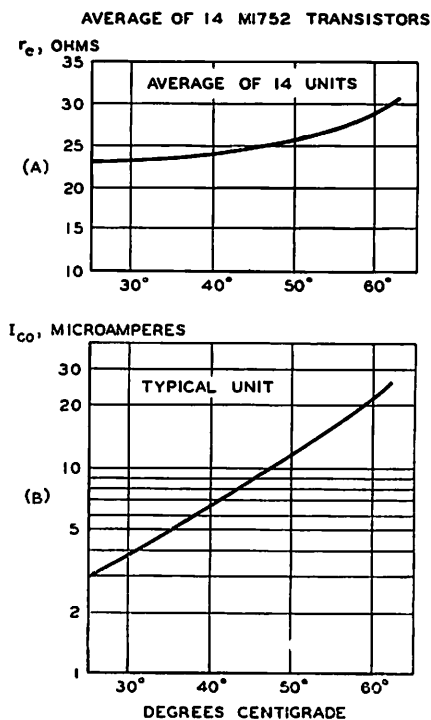


Fig. 11—Effect of temperature on r_e , I_{co} .

temperature range are given in Figs. 10 and 11. The saturation current varies much more widely than the other parameters. The reduction in slope of the curve of Fig. 11(B) at low temperature is considered to be the result of ohmic leakage across the junction.

Figure 12 summarizes noise measurements for 12 junction transistors in the low and carrier frequency range. It is evident that for quiet operation the collector bias should be low. Though not shown in Fig. 12, there is some evidence that the optimum noise figure will be obtained at low emitter currents, in the order of 0.1 ma, when the collector bias is in the order of 1 volt.

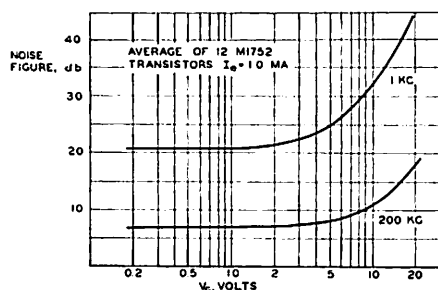


Fig. 12—Average noise figure vs. V_c .

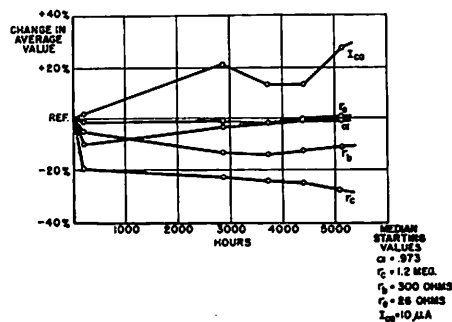


Fig. 13—Early life data, development model n-p-n transistors.

At frequencies below 50 kc, the noise spectrum appears to be of the form^c $p(f) = K/f^{1.2}$. As the frequency is increased above 50 kc, some units continue to follow the above relation, while others show several db less improvement than would be expected.

IV. RELIABILITY OF JUNCTION TRANSISTORS

The construction of the junction transistor by welded or soldered connections to crystalline germanium should allow an almost indefinitely long life for the device. Theory and experiment indicate that the bulk properties of the germanium are stable at normal working temperatures. Thus the life should be limited only by the degree of mechanical and chemical protection which can be provided. It is especially important that the germanium surface be protected from chemical action. Improper surface conditions result in increased shunt leakage, higher saturation current, and lower alpha.

Although not enough information is at present available to make accurate life estimates of junction transistors, some early results are indicated in Fig. 13. Thirty-five development model M1752 units were placed on life test. Two of these units were accidentally destroyed in subsequent testing operations, but none has failed on the life rack, after slightly more than 5,000 hours operation. The changes of average value of α , r_e and saturation current shown in Fig. 13 are in the direction of poorer performance, while the reduction of average r_b is an apparent improvement, which may be largely due to the reduction of r_c , as indicated in (10).

^cThe subject of transistor noise will be treated in detail by H. C. Montgomery in an article to be published in *Proc. I.R.E.*, November, 1952.

V. JUNCTION TRANSISTORS IN POWER APPLICATIONS

The M1752 transistor is designed for low power applications at low and moderate frequencies, and has a nominal power dissipation rating of only 50 milliwatts. It is of interest to consider some of the possibilities and limitations of the same basic $n-p-n$ structure, when designed for applications which require the transistor to dissipate appreciable power. In this respect the junction transistor has a fundamental advantage over the point contact transistor in that the heat source is not concentrated in the vicinity of a small collector point but is distributed over the area of the collector junction.

It will become evident early in an analysis of the heat dissipation problems of germanium transistors that heat dissipation by radiation cannot play the important part which it does in low and medium power vacuum tubes. The available temperature differences between the transistor and its environment are low, since the maximum temperature of the semiconductor must be held to perhaps 70°C . This in turn means that the power radiated per square cm of area will be very low indeed.

When we turn to conduction cooling, the outlook is more promising. Germanium, fortunately, has a thermal conductivity of about 0.125 in the temperature range of interest, which is about the same as the thermal conductivity of brass. If all the power dissipated in the transistor were assumed to appear as heat at the collector junction and to be conducted to a heat sink at one end of the transistor, the temperature rise at the junction would be

$$(19) \quad \Delta T = \frac{.24Wl}{\sigma A} = 1.92 \frac{Wl}{A}$$

where σ = Thermal conductivity of Germanium

= 0.125 cal/ $^{\circ}\text{C}$ at 55°C

A = Area of germanium bar

W = Power dissipated in watts

l = Length of germanium between junction and heat sink.

In a practical case it will not be possible to hold the heat sink at ambient temperature, and some allowance must be made for the thermal impedances external to the transistor.

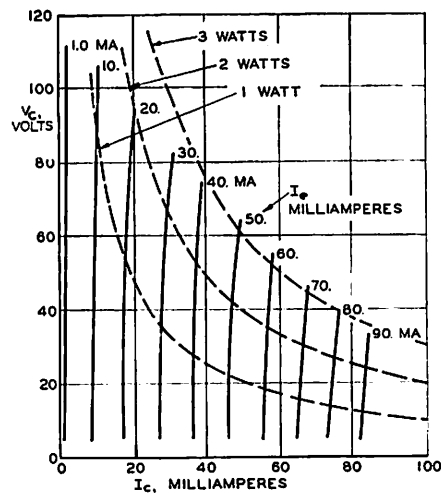


Fig. 14—Static characteristics, development model power transistor.

Since the total temperature rise must be kept small, extreme measures are in order to reduce thermal impedance wherever possible.

The right hand transistor illustrated in Fig. 1 is a development model designed for power dissipation in the order of three watts. Representative static characteristics are shown in Fig. 14. This model is intended to be mounted in direct contact with a metal chassis or other thermal sink. Class A power output of one watt may be obtained at a collector potential of 60 to 80 volts at an efficiency of 33 per cent. The distortion at this power level is in the order of eight per cent, and the power gain is 26 db. It is noted that some compensation of input and output distortion is obtained by making the generator impedance low.

VI. CONCLUSIONS

While junction transistors have not as yet been produced in large numbers, results obtained in the measurement of several hundred development model $n-p-n$ transistors indicate that such production is practicable. The foundation of design theory is on relatively firm ground, in that performance of devices may be predicted to a reasonable accuracy when the characteristics of the starting material are known.

Early results of life tests indicate a long useful life, but data are available for only five thousand hours operation.

As diverse applications arise, it will be possible to design for special performance qualities, as higher power, extreme miniaturization, higher voltage, lower capacitance, or higher frequency.

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2108: K. D. SMITH

BELL TELEPHONE LABORATORIES, *incorporated*

463 West Street, New York 14, N. Y.